# NGST NIRCam Scientific Program and Design Concept

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**ABSTRACT**

The science program for the Next Generation Space Telescope (NGST) relies heavily on a high performance near-infrared imager. A design which supports the observations outlined in the Design Reference Mission (DRM) and which also supports enhanced searches for "first light" objects and planets has been developed. Key features of the design include use of refractive optics to minimize the volume and mass required, tunable filters for spectroscopic imaging, and redundant imagers for fail-safe wavefront sensing.

**Keywords:** Next Generation Space Telescope, near-infrared camera

## 1. INTRODUCTION

The Next Generation Space Telescope (NGST) has as it most ambitious goal the detection of the first objects to coalesce and emit light after the Big Bang, the “First Light” objects. It will also serve as a general observatory much in the style of the Hubble Space Telescope (HST), and must be capable of addressing a broad range of observations. The power of NGST comes from its large light collecting power, its location in space above atmospheric interference, and its instruments which analyze the light it collects. NGST’s near-infrared camera, nicknamed NIRCam, is an essential part of its instrument complement having been given top priority in the NGST Ad-Hoc Science Working Group’s consideration of instrumentation for NGST.

## 2. NIRCAM REQUIREMENTS

The broad outline of NIRCam’s capabilities were defined by the “Design Reference Mission” which identified a suite of observations that NGST must be capable of performing. The capabilities of our NIRCam implementation are listed in Table 1.

### 2.1 Extragalactic Science Requirements

To achieve the goal of finding “First Light Sources” and to provide deep images where galaxy evolution can be studied, NIRCam needs as large a field of view as is practical. Exposure times will of necessity be long because of the faintness of these distant objects, and enough sky must be observed at once to ensure finding what may be rare objects. Figure 1 illustrates what is likely to be observed by NIRCam in very deep (50,000 second) exposures based on what we

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| Table 1: NIRCam Capabilities | |
|---|---|
| Wavelength Range | 0.6-5.0μm |
| Spectral Resolutions | Selection of R~4 and R~10 discrete filters, R~100 using 2 tunable filters |
| Fields of View | Imaging: 2.3'x4.6' at two wavelengths simultaneously<br>R=100 Imaging: Two 2.3'x2.3' fields (one λ<2.5μm, one λ>2.5μm) |
| Spatial Resolution | Imaging: 0.034 "/pixel λ<2.5μm<br>0.068 "/pixel λ>2.5μm<br>R=100: 0.068 "/pixel |
| Coronagraphy | Choice of coronagraphic spots and pupils in all instrument sections |

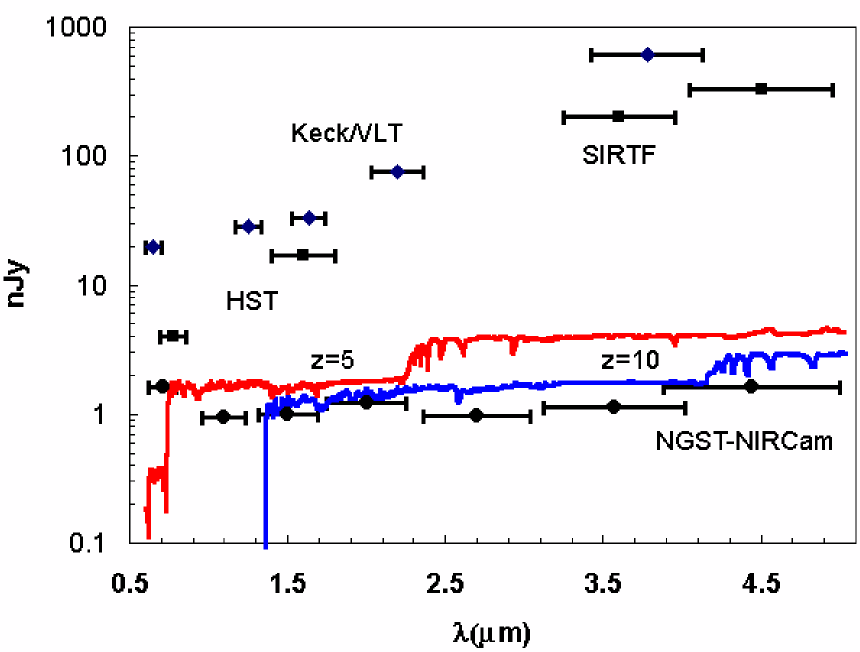


Figure 1: Detectability of high redshift galaxies (5-σ in 50,000 sec) for a variety of existing and future observatories. The z=5 galaxy has $M=2x10^9\ M_{Sun}$ and an age of 900 Myr. The z=10 galaxy has $M=2.4x10^8\ M_{Sun}$ and an age of 30 Myrs.

know about galaxies now. Surveying efficiency is consequently very important. Our design uses dichroics to enable simultaneous observation of a field at λ<2.4μm and at λ>2.4μm. The camera will also need excellent spatial sampling as the distant galaxies are likely to have small angular extents, ~0.1" based on HST experience[1]. NIRCam will be able to detect objects too faint for study from the ground or with NGST's spectrometer and must therefore also include a complement of filters that enables photometric redshift estimation. Last, we must realize that we know very little about the character of "First Light Sources". Will the first light be produced by accretion onto black holes or by stars? Will objects be clustered or single? What we do know is that hydrogen gas will be abundant and any technique to search for gas ionized by "First Light" objects will enhance our probability of finding these objects. Our NIRCam design includes tunable filters for searching for the first Lyman-α sources.

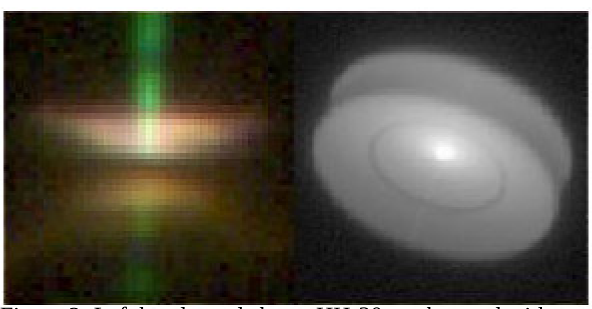

Figure 2: Left hand panel shows HH-30 as observed with WFPC2 on HST[2]. The right hand panel shows how an object 10 times fainter and not edge-on would appear to NIRCam at 2μm with the central star's intensity reduced by use of its coronagraph. The simulation includes shot noise, pointing jitter, and realistic telescope parameters.

**2.2 Galactic Science Requirements**

NGST will also be a premier tool for studying star and planet formation within our own galaxy. The extragalactic survey requirements lead to a camera that is also an excellent tool for a variety of star formation studies. The sensitivity and field of view support investigating the low mass initial mass function in a variety of environments, for example.

For studying either exo-planets or circumstellar disks, our camera design includes coronagraphs in all modules.

This capability has been implemented without requiring any additional mechanisms. A choice of coronagraphic occulting spots of varying sizes are located along the sides of the regular fields of view at the location of the field pickoff mirrors in the telescope's focal plane. The pupil wheel for each module includes a choice of coronagraphic pupils each of which includes a field offset wedge that brings the coronagraphic spots in the focal plane into the field of view of the module's array. Use of the coronagraphic mode in the tunable filter modules will enable low resolution spectroscopy of planets around other stars, an observation not possible with NGST's spectrometer which has no coronagraphic capability.

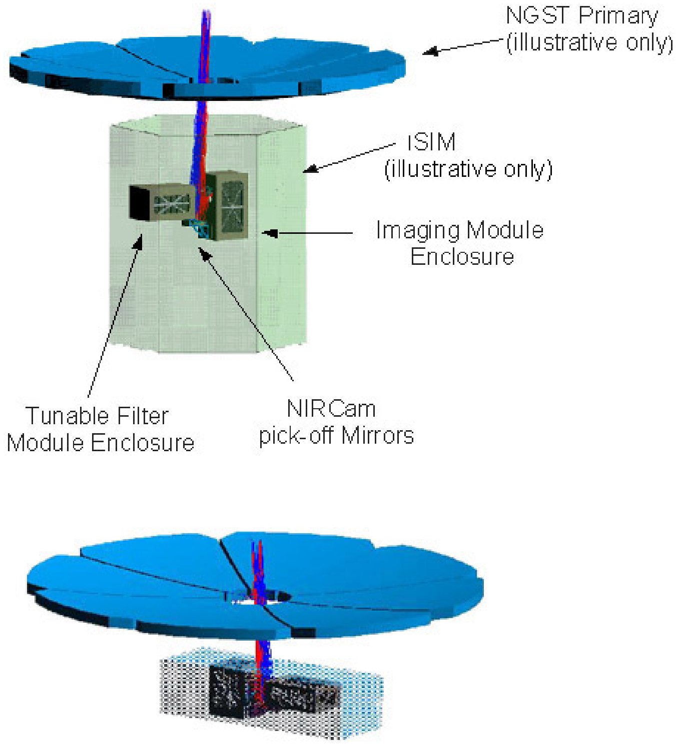


Figure 3: NIRCam shown in the NGST Integrated Science Module (ISIM). Lower portion illustrates the compactness of the refractive design as compared to NIRCam's allocated volume in the ISIM shown as the shaded volume.

**2.3 Wavefront Sensing Requirements**

In addition to its role as a science imager, NIRCam also has to produce the image data used for wavefront sensing on NGST. The NGST primary will be deployed after launch, and the camera not only has to be able to take images for initial capture of the mirror segments, but must also take images for maintaining alignment throughout the lifetime of NGST. These roles place additional, critical constraints on the NIRCam design. First, the camera must accommodate extra optics and pupil analyzers to enable the wavefront sensing. Second, the modules incorporating the wavefront sensing must be fully redundant as the mission depends critically on this functionality. Our NIRCam design includes two identical imaging modules each of which includes dual filter wheels. The dual filter wheels are configured so that one wheel holds bandpass filters while the other wheel holds pupil analyzers thus permitting wavefront analysis as a function of wavelength. Since wavefront sensing does not use all of the locations in the pupil wheel, adding coronagraphy is straightforward using the extra pupil positions.

## 3. NIRCAM DESIGN FEATURES

NGST will be placed into an orbit at L2 and hence as is typical with space instruments, mass and volume are at a premium. The early designs studies for a near-infrared camera for NGST[3] relied on all reflective optical designs. The dimensions of the Integrated Science Module (ISIM) were sized to accommodate a reflective NIRCam. We explored a refractive design for NIRCam to see whether the wavefront quality and throughput could be maintained while producing a significantly smaller NIRCam. Figure 3 shows the positioning of NIRCam within the ISIM and that the refractive design occupies only about 1/3 of the volume allocated for it. The design also meets the requirement on wavefront quality with wavefront errors of 16nm at 0.8 μm, plenty of margin relative to the 56nm requirement..

Use of refractive optics for a space instrument, especially one with very stringent requirements on dark currents, places an additional burden of proof on the instrument fabricators. Experiences such as those with the corrector plate for WFPC2 must be avoided where scintillation in the plate essentially increase the dark current.. Figure 4 shows one of the imaging modules and illustrates that the solid angle of the lenses closest to the focal plane arrays is much smaller than in

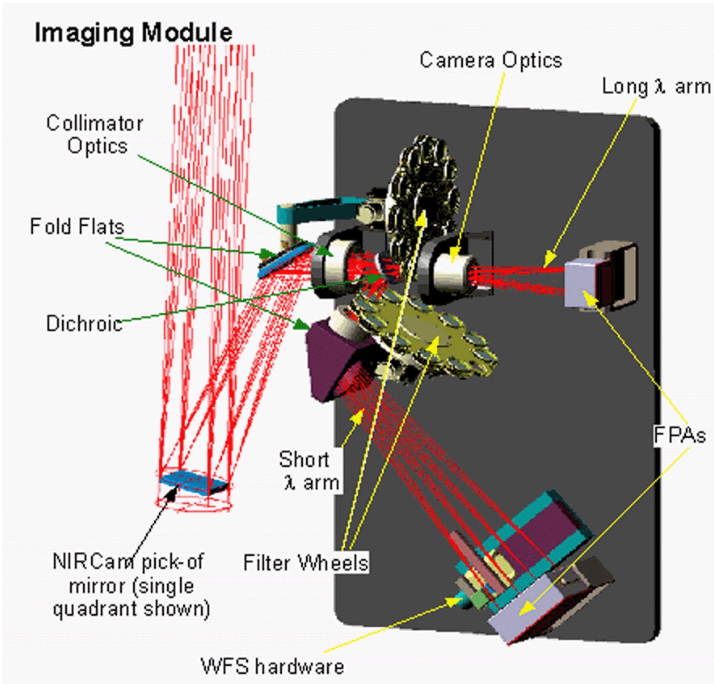

Figure 4: Layout of a NIRCam imaging module. The tunable filter modules are similar.

the case of the corrector plate for WFPC2. We have tested a few candidate lens materials for scintillation over the 1.1 to 2.5μm range. No scintillation was observed to a level corresponding to < 0.001 /second assuming the view factors in our design. This is below the detector dark current. Nonetheless, further screening at 2.5 to 5 μm is needed as will be screening of samples of the actual materials to be used. A number of candidate lens materials have been used in space such as in the Infrared Space Observatory and on the Long Duration Exposure Facility with no degradation in transmission within the 1.5% measurement errors[4].

Another feature of our NIRCam design is the use of dichroics. This permits observation of a field at two wavelengths at once which has several benefits. The short wavelength and long wavelength plate scales can be optimized separately. Our short wavelength module is Nyquist-sampled at 2μm while the long wavelength module is Nyquist-sampled at 4μm. Observation of two wavelengths at once also increases observing efficiency. Table 2 summarizes the characteristics of the NIRCam modules.

Table 2: NIRCam Module Characteristics

| | Imaging Module 1 | Imaging Module 2 | Tunable Filter Module Short λ | Tunable Filter Module Long λ |
|---|---|---|---|---|
| Wavelength range (μm) | 0.6 to 2.3<br>2.4 to 5 | 0.6 to 2.3<br>2.4 to 5 | 1.2 to 2.5<br>1 to 2.5 goal | 2.5 to 4.5<br>2.3 to 5 goal |
| Nyquist λ (μm) | 2 / 4 | 2 / 4 | 4 | 4 |
| Pixel Format | $4096^2$ (short λ)<br>$2048^2$ (long λ) | $4096^2$ (short λ)<br>$2048^2$ (long λ) | $2048^2$ | $2048^2$ |
| Field (arc min) | 2.3 x 2.3 | 2.3 x 2.3 | 2.3 x 2.3 | 2.3 x 2.3 |
| Spectral Resolution | 4, 10 | 4, 10 | 100 | 100 |

## 4. NIRCAM FILTER SELECTION

A key task for NIRCam is identification of the most interesting high redshift galaxy candidates. NIRCam surveys will become the backbone of the "First Light" searches and for galaxy evolution studies. Deciding what is likely to be a "First Light" source rather than a peculiar low redshift object will depend on having good redshift information. Selection of galaxy samples for further study with NGST's spectrometer and mid-infrared instrument (MIRI) also depends on good redshift estimation. NIRCam includes a set of broadband filters whose wavelengths and widths have been carefully chosen to support accurate photometric redshift estimation.

The filter set was optimized by considering sensitivity, redshift estimation, and calibration. Extremely broad filters can detect very faint objects but are very difficult to calibrate because knowledge of the input spectral energy distribution is needed to correct the photometric measurement for the spectral slope across the filter[5]. Too few filters across an object's spectral energy distribution is also bad, especially for accurate redshifts. By creating synthetic samples of galaxies distributed in redshift in a manner appropriate for NGST[6] and creating photometric catalogs using trial sets of filters, the efficacy of photometric redshift estimation could be tested as shown in Figure 5. The higher sensitivity for R=4 filters offsets the better spectral resolution of the R=5 filters while R=3 suffers from too few filters for good redshift estimation. The adopted observing strategy uses seven filters (B1 through B7 in Table 3) with double exposure time given to B7 at 4.4μm. The improvement brought about by this doubling can be seen in Figure 5 by comparing the vertical bars showing the results for the adopted survey strategy with the horizontal bars for R=4 and 7 filters.

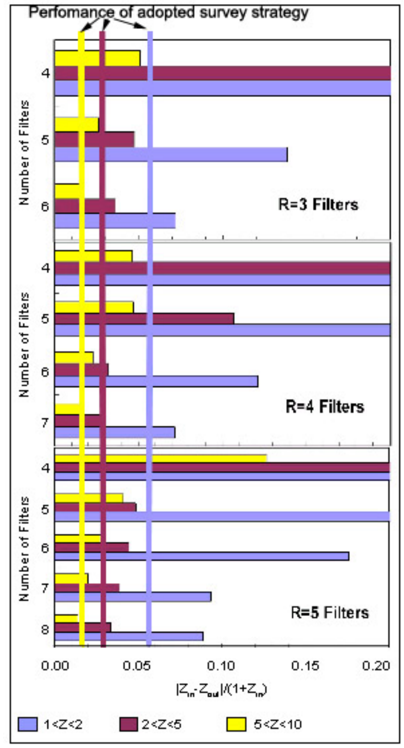


Figure 5: The fractional error in photometric redshift estimation as a function of number and width of filters. The vertical bars show the accuracies achieved using an R=4 filter set and seven filters with the longest wavelenght getting twice the exposure time.

NIRCam also includes intermediate band filters to aid in the identification of solid state features that might arise in spectra of circumstellar disks or from solar system objects. Figure 6 illustrates the power of the NIRCam filter set for diagnosing ices, PAHs, and cool star spectral features. The coronagraph combined with these filters will enable detailed characterization of disks such as those around stars like HR4796 and will clarify whether such disks are related to the solar system's Kuiper Belt.

Table 3 lists all of the NIRCam filters and pupil choices. All of NIRCam's filter wheels are identical, 12-position dual wheels. Note that some of the pupil entries such as the outward pinholes are used during construction of NIRCam for alignment tests. Most of the filters in the tunable filter modules are order blocking filters while the 1% filters will be used to supplement the NIRCam complements as back-ups to the tunable filters. The flat field source positions bring an illuminator into the pupil so that internal flat fields can be taken in a manner analogous to the NICMOS internal lamp flats. These same positions allow dark frames to be taken with the illuminator switched off.

## 5. DETECTORS AND CALIBRATION

The detectors for NIRCam have not been selected yet but will either be HgCdTe with a 5μm long wavelength cut-off or InSb, both photo-diodes. The HgCdTe will have similar properties to the NICMOS detectors while the InSb is related to the detectors in the IRAC instrument for SIRTF. The readout multiplexers would be similar in either case and will allow non-destructive reads. Either type will also include reference pixels for tracking DC drifts. The basic focal

Table 3: NIRCam Filters and Pupils

| | **Imaging -Short** | | **Imaging -Long** | | **Tunable Filter** | |
|---|---|---|---|---|---|---|
| Position | Filter wheel | Pupil wheel | Filter wheel | Pupil wheel | Filter wheel | Pupil wheel |
| 1 | B1-0.7μm | Imaging pupil | B5-2.7μm | Imaging pupil | Blocker-1 | Imaging pupil |
| 2 | B2-1.1μm | Flat field source | B6-3.6μm | Flat field source | Blocker-2 | Flat field source |
| 3 | B3-1.5μm | Outward pinholes | B7-4.4μm | Outward pinholes | Blocker-3 | Outward pinholes |
| 4 | B4-2.0μm | Coron pupil 1 | I4-2.4-2.6μm | Coron pupil 1 | Blocker-4 | Coron pupil 1 |
| 5 | I1-1.55-1.7μm | Coron pupil 2 | I5-2.8-3.2μm | Coron pupil 2 | Blocker-5 | Coron pupil 2 |
| 6 | I2-1.7-1.95μm | HeI 1.083μm | I6-3.2-3.5μm | TBD | Blocker-6 | Cal Pattern 1 |
| 7 | I3-2.0-2.22μm | WFS-1 | I7-$CO_2$ 4.3μm | TBD | Blocker-7 | Cal Pattern 2 |
| 8 | B8-0.8-1.0μm | WFS-2 | I8-CO 4.6μm | TBD | Blocker-8 | Cal Pattern 3 |
| 9 | Hα0.656μm | WFS-3 | Brα 4.05μm | TBD | Blocker-9 | Cal Pattern 4 |
| 10 | [FeII] 1.64μm | WFS-4 | $H_2$ 2.41μm | TBD | 1%-1 | TBD |
| 11 | Pα 1.875μm | WFS-5 | $H_2$ 2.56 μm | TBD | 1%-2 | TBD |
| 12 | $H_2$ 2.12μm | WFS-6 | $H_2$ 4.69μm | TBD | 1%-3 | TBD |

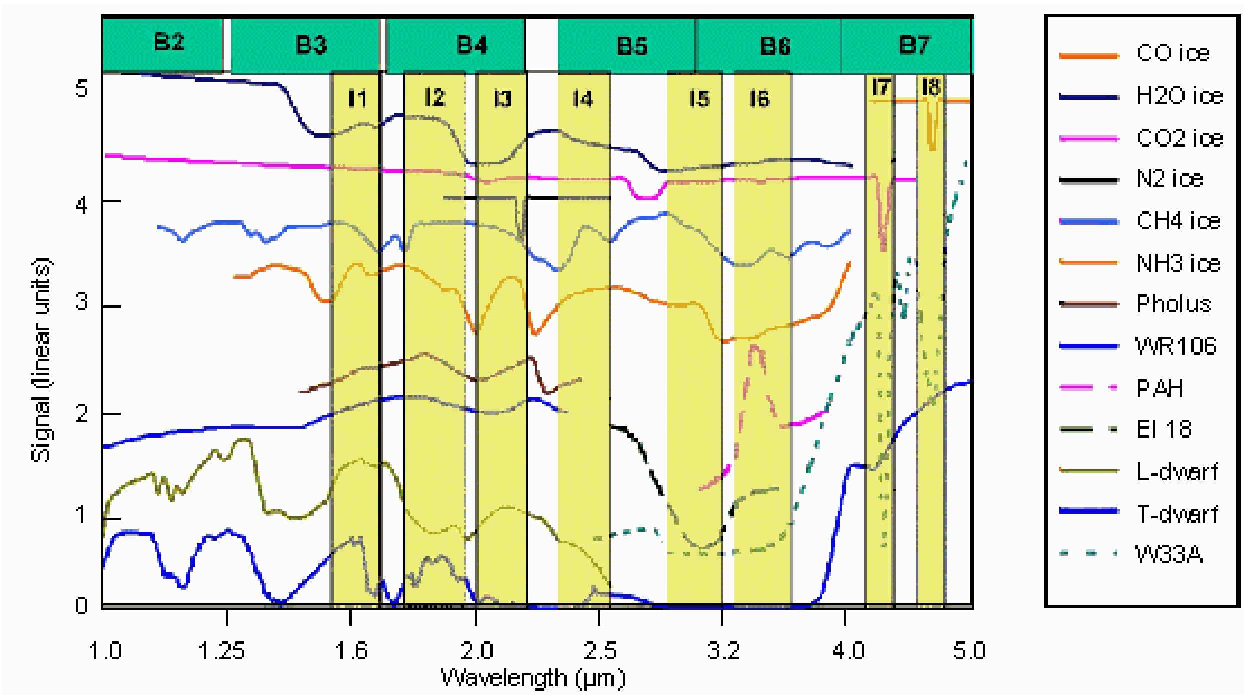


Figure 6: NIRCam filters can diagnose whether objects are very cool such as L or T dwarfs or whether they have any of a variety of ices or PAHs.

array format will be 2048x2048 pixels regardless of detector type. Either of the NIRCam array choices will have a space flight heritage from NICMOS or IRAC with readout strategies relatively well understood.

Because of the similarities between the NIRCam detectors and those in NICMOS and IRAC, the essential calibration plan can be largely based on the plans for those instruments. Dark frames and flat fields using NIRCam's internal features can be taken in a manner analogous to what is done with NICMOS and what would have been done with IRAC if it could use its shutter. The backgrounds that NIRCam will see will be very low but for some data sets, flat fields can be derived by combining dithered images. The tunable filter modules will need to rely exclusively on the internal flat field source.

The photometric calibration will be generated using observations of solar analogue stars as was used for NICMOS. This technique[7] is based on using knowledge of the solar spectrum to fill in the gaps between groundbased observations of solar-type stars. The only challenge for NIRCam is in selecting suitable stars because of the relatively long minimum exposure time of 10 seconds. Three well studied clusters (NGC2420, NGC2506, and NGC6791) have been selected on the basis of having low extinction, close to solar metallicity, and being at the correct distance for solar type stars to have K(2.2μm) fainter than 15$^{th}$, the required level to match the detector well depths and minimum exposure time. These same clusters can be used to derive the astrometric calibration of NIRCam.

The tunable filters will have a flux calibration derived in the manner described above. The wavelength calibration will be based on observations of objects like planetary nebulae and HII regions where an adequate number of strong lines are known. Observations using the NICMOS narrowband filters (R=100) illustrate that there will be no lack of candidate calibrators.

## 6. NIRCAM TEAM SCIENCE PROGRAM

The NIRCam team has designed the instrument to support the observations required in the DRM and their own observing program which overlaps the DRM. The team science program is concentrated in three areas: 1) the formation of galaxies from the first lighting emitting objects to the development of the Hubble sequence of galaxies as we know them today; 2) the formation of stars and brown dwarfs including tests of what fundamental parameters control the star formation process; and 3) the characterization of planetary systems from birth to maturity including spectroscopy of planets around other stars.

**6.1 Galaxy Formation Program**

The heart of our galaxy formation program is a deep survey using 50,000 second exposures in each of six filters and 100,000 seconds for the 4.4μm filter. The sensitivities in Figure 1 relative to spectral energy distributions for hypothetical z=5 and z=10 galaxies are based on such a survey. While the broadband survey is being conducted in the two imaging modules, the tunable filter modules will be carrying out an emission-line survey on an adjacent piece of sky. Repeating the exposures six months later when the field will have rotated by 180 degrees due to NGST's orbital motion around the sun will yield emission line data on the original broadband fields and vice-versa. The emission line survey will sub-divide the long broadband exposure times into a series of 3000-second exposures split over wavelength settings that cover a range in redshift. The complete suite of wavelengths for each possible redshift for Lyman α will include two extra settings to observe other lines such as that corresponding to the redshifted wavelength for HeII at 1640Å and either for Hβ or for Pβ. This strategy will guard against detecting a strong line and assuming that is is Lyman α when the line is actually Hα at a much lower redshift. The long wavelength tunable filter module will be used in a search for moderately redshifted Hα (z~2.8 to 5.9). Two 4.6'x4.6' fields will be surveyed and will be selected from the deep fields studied with SIRTF and Chandra.

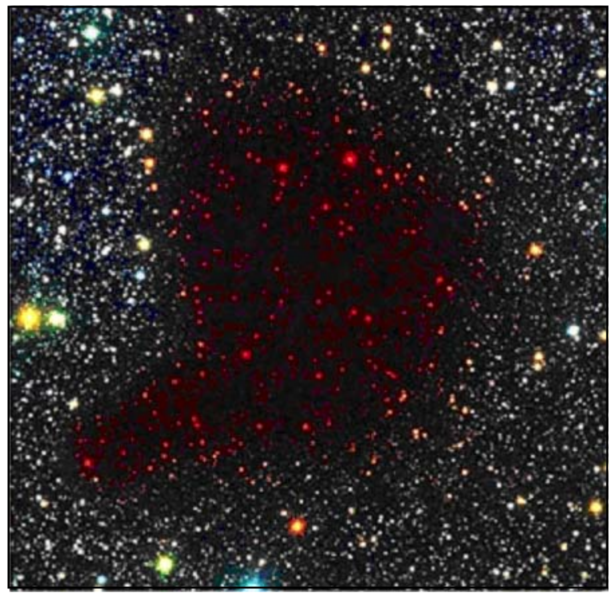

Figure 7. B, I, K image of Bok Globule 68 with the VLT[8]. Background stars are detected at K (red); measurements of their extinction probe the density distribution in the globule. FOV is 4.9’x4.9’.

**6.2 Star Formation Program**

This portion of our observing program addresses three fundamental issues in star formation: 1) What physical variables determine the shape of the IMF?; 2) How do cloud cores collapse to form isolated protostars?, and 3) Does mass loss play a crucial role in regulating star formation? We will address the first issue by determining the initial mass function as a function of metallicity, and whether there is a limit on the low mass end of the initial mass function imposed by opacity and cooling limits. The second issue will be addressed by measuring the density profiles in dense molecular clouds by using NIRCam's sensitivity from 2 to 5μm. Color-color diagrams can be constructed which in term yield extinction profiles from which density profiles can be computed. Figure 7 illustrates the detection of background stars seen through Bok Globule 68. The third issue will be addressed by surveying young clusters already known to harbor protostars. The survey will indicate which objects have excess emission indicative of disks. Water or PAHs will also be detectable from the survey data. Objects for more detailed imaging in emission lines will be chosen from the survey with a goal of distinguishing accretion from outflows.

**6.3 Debris Disk and Planetary System Program**

This portion of the NIRCam Team's observing program seeks answers to questions such as 1)What are the initial conditions for formation of debris disks?, 2) How do these disks evolve in structure and composition?, 3) How do Kuiper Belt Object (KBO) surface compositions compare with debris disks?, 4) Do giant planets orbit nearby stars?, and 5) How do they relate to the debris disks? We will study circumstellar disks from their formation through their evolution to debris disks. NIRCam's coronagraph will enable detection of the reflected light from a broad range of disk densities. Combining NIRCam data on the reflected light from disks with the thermal emission from disks as measured by MIRI and by SIRTF at even longer wavelengths will allow us to build up a picture of the nature and distribution of dust from 1 AU out to beyond 100 AU. Selected disks will be imaged using the coronagraphic mode of the tunable filter modules permitting the composition measurements of disks selected for being in a range of evolutionary states. Comparison of

KBOs with disks will begin with observing a suite of bright KBOs in detail to develop a set of KBO template spectra. A subset of these KBOs will be observed at 24μm to determine radii and albedos which can be correlated with surface spectral features. The last questions will be addressed by discovering and studying planets around stars selected in three complementary ways. First, planets around nearby stars will be studied where Jupiter-sized objects lying 4 to 10 AU from parent stars can be studied. Second, planet searches will conducted on stars with known debris disks such as ε Eri and α Lyrae where millimeter wave and other data suggest that planets must be present. The third planet search will be conducted on stars thought to be young on the basis of spectral or kinematic data. All of these searchs rely on the NIRCam's coronagraphs. The atmospheres of detected planets will be further using NIRCam's intermediate band filters and the tunable filters.

## 7. ACKNOWLEDGMENTS

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## 8. REFERENCES

1. J. Gardner and S. Satayapal, "Counts and Sizes of Galaxies in the Hubble Deep Field - South: Implications for the Next Generation Space Telescope", *AJ*, **119**, pp.2589-2597, 2000.
2. K. Stapelfeldt, A. Watson, J. Krist, C. Burrows, D. Crisp, G. Ballester, J. Clarke, R. Evans, J. Gallagher, R. Griffiths, J. Hester, J. Hoessel, J. Holtzman, J. Mould, P. Scowen, and J. Trauger, "A Variable Asymmetry in the Circumstellar Disk of HH 30", *ApJL*, **516**, pp. L95-L98, 1999.
3. R. Burg, P. Bely, R. Woodruff, J. MacKenty, M. Stiavelli, S. Casertano, C. McCreight, C., and A. Hoffman, " " 'Yardstick' Integrated Science Instrument Module Concept for NGST", *Proc. SPIE*, **3356**, pp. 98-105, 1998.
4. G. Hawkins, "PHD Thesis - The University of Reading, Department of Cybernetics", 1998.
5. F. Low, and G. Rieke, "Instrumentation and Techniques of Infrared Photometry", *Methods of Experimental Physics*, **12A**, pp. 415-462, 1974.
6. A. Loeb, and R. Barkana, "The Reionization of the Universe by the First Stars and Quasars", *AnnRevA&A*, **39,** pp. 19-66, 2001.
7. H. Campins, G. Rieke, and M. Lebofsky, "Absolute Calibration of Photometry at 1 through 5μm", *AJ*, **90**, pp. 896-899, 1985.
8. J. Alves, C. Lada, and E. Lada, "Internal Structure of a Dark Molecular Cloud Inferred from the Extinction of Background Starlight", *Nature*, **409**, pp. 159-161, 2001.